Summing Logs for Fun and Profit: Tools for Jet Physics

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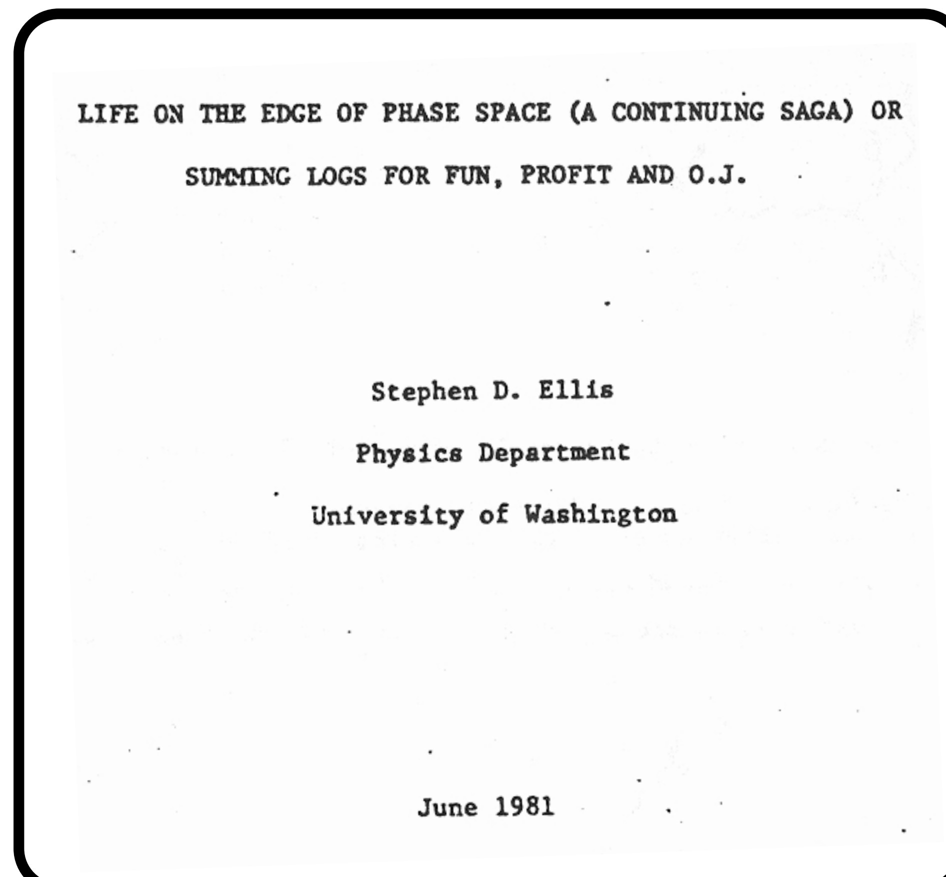
UC Berkeley, LBL

Outline

- What this talk is about:
  - Approaches to study jet physics - in particular, detailed properties of jets
  - Open problems in SCET and jet physics
- What I will provide: questions
- What I won't provide: answers

Summing Logs for Fun and Profit, redux



LIFE ON THE EDGE OF PHASE SPACE (A CONTINUING SAGA) OR

SUMMING LOGS FOR FUN, PROFIT AND O.J.

Stephen D. Ellis

Physics Department

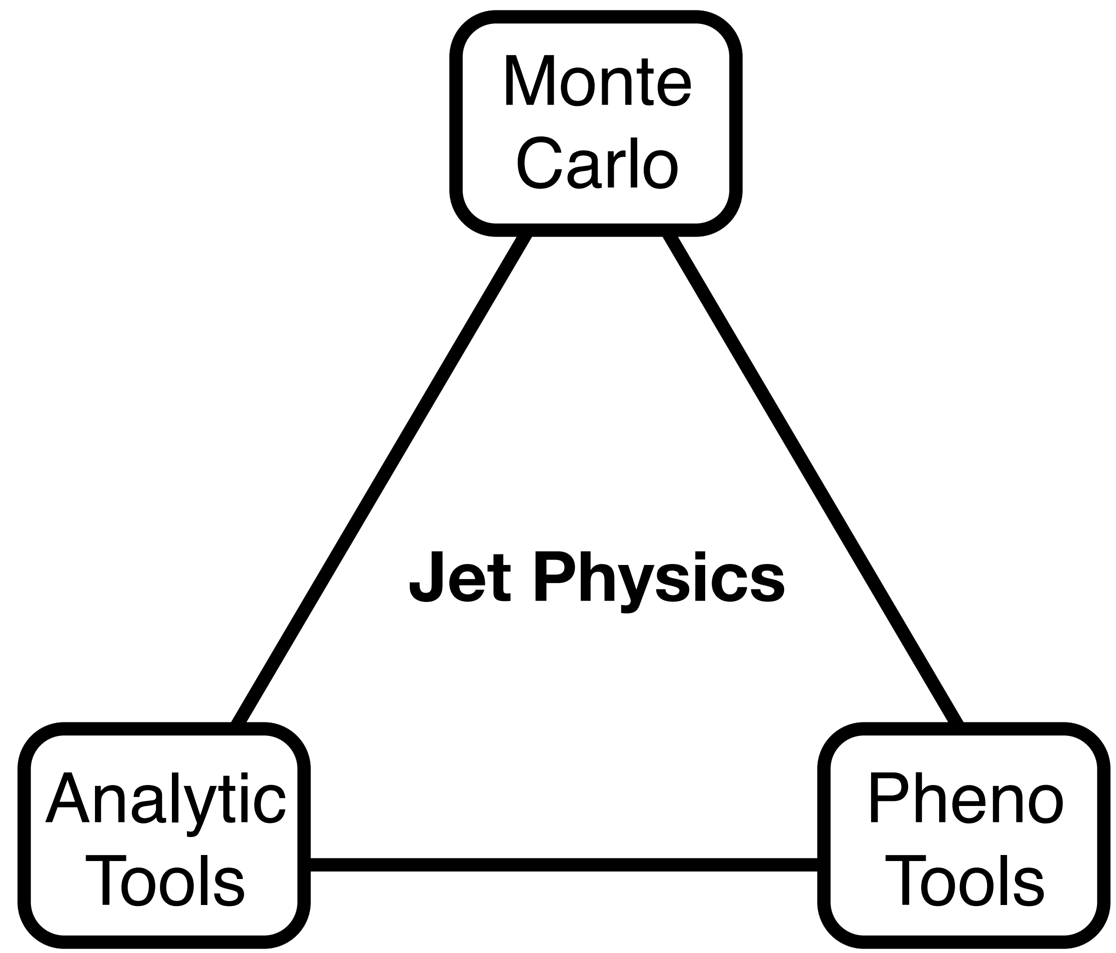
University of Washington

June 1981

Tools for Jet Physics

Three main tools used to study jets:

- Monte Carlo: simulate perturbative QCD, entire events
- Pheno Tools: devise analysis techniques to differentiate between different processes
- Analytic Tools: calculate distributions of observables for jets and events



Monte Carlo

Pros:

- Standard tool for studying jets, well tested history
- Provides a basis for validation and comparison of ideas
- A lot of physics is in the MC that is otherwise hard to access (hadronization, MI/UE, pileup)

Cons:

- A lot of physics crucial to the details of jets isn't in the MC
  - Leading-log, leading-color parton showers only
  - NLO not widely implemented
  - Matching not well tested

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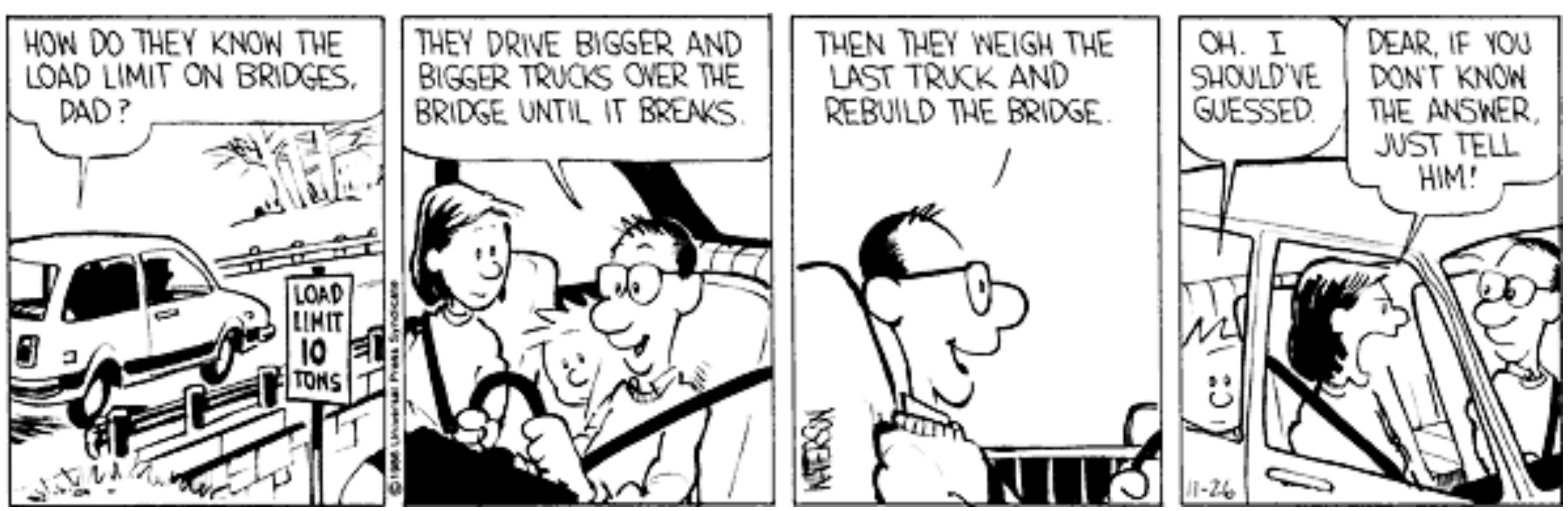


from Steve Mrenna

Q: How do we know the bridge is still intact?

A: Wait for experimental studies to tell us

Pheno Tools

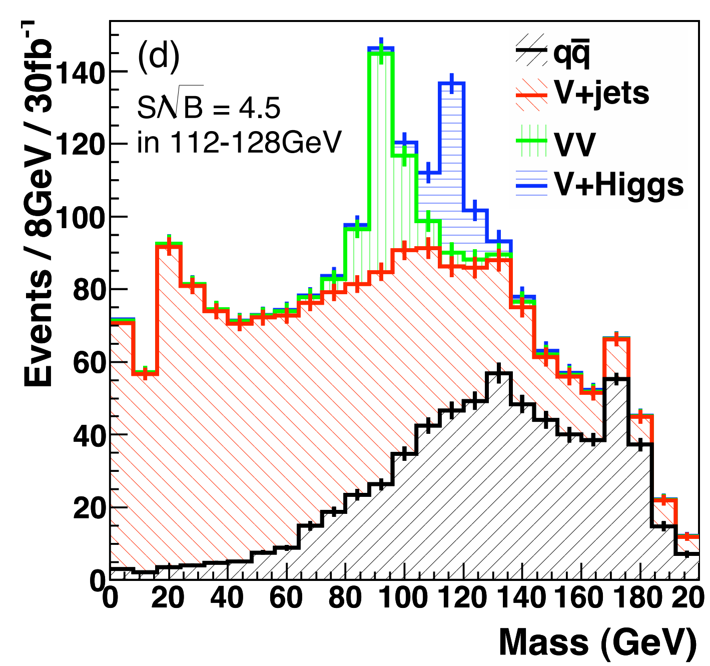
Examples: jet substructure for QCD jets and BSM searches

Pros:

- Can build powerful analysis tools to identify a wide range of signatures
- Tractable approach to complex dynamics of jets
- Bridges the gap between theory and experiment
- Success in approaching complex jet environment at LHC

Cons:

- Relies on largely qualitative understanding of jet evolution
- Difficult to verify tools will work in experimental analyses - needs accurate Monte Carlo modeling



Butterworth, Davison, Rubin, Salam

$h \to b\bar{b}$ via jet substructure

Analytic Tools

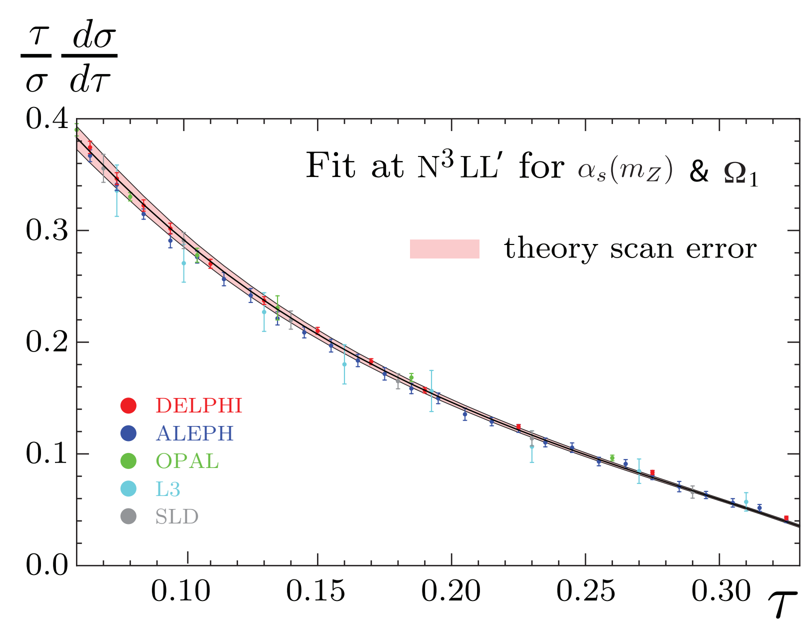
Examples: effective field theories for QCD at high energies

Pros:

- Provides a rigorous framework to understand jets, jet evolution
- Allows a description of the jet algorithm and effects on an observable
- Capable of obtaining high accuracy in predictions
- Effective theory a useful guide for phenomenological understanding

Cons:

- Difficult to access experimentally interesting observables - analytic approaches not well-developed
- Can be difficult to account for non-perturbative physics



Abbate, Fickinger, Hoang, Mateu, Stewart

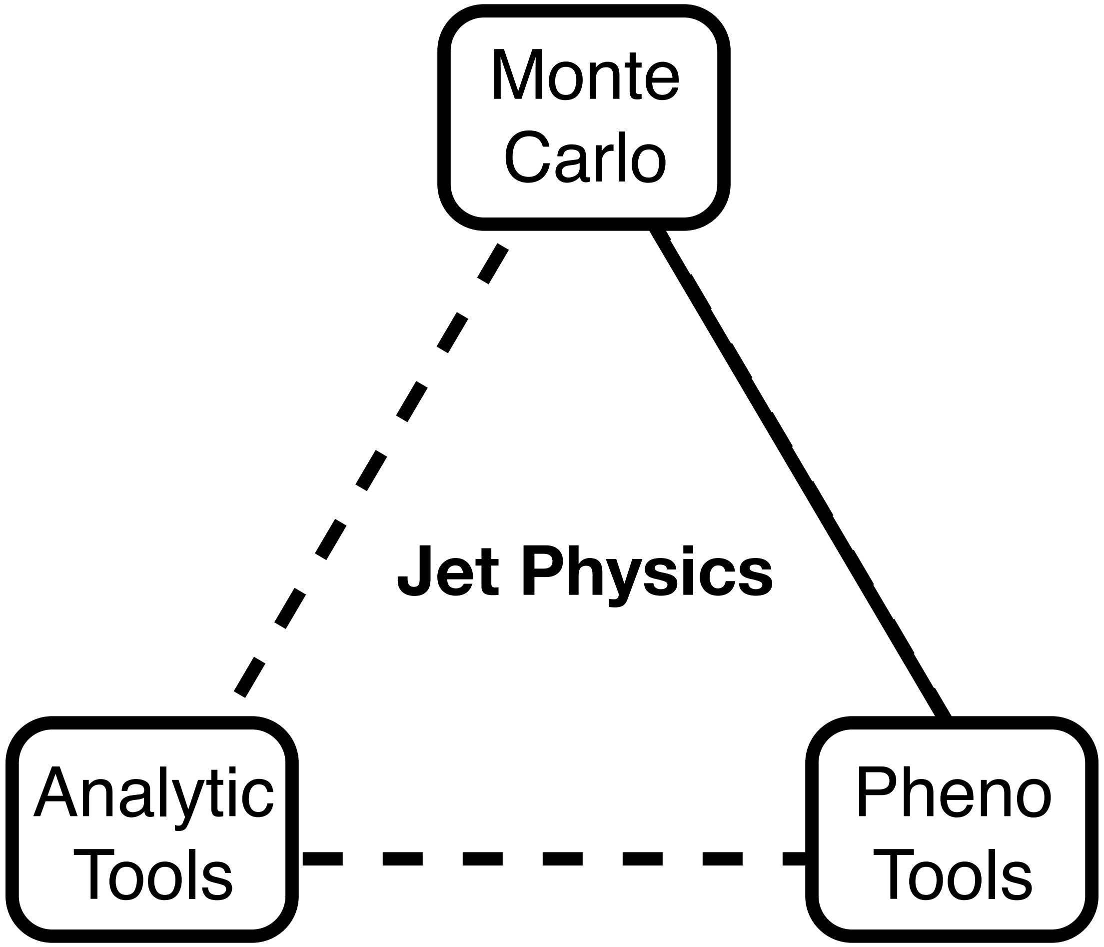
N^{3}LL extraction of α_s

Tools for Jet Physics

Needs:

- Monte Carlo: more complete description of perturbation theory
- Pheno Tools: more robust MC testing, better framework to understand all aspects of jets
- Analytic Tools: wider applicability to physically relevant events

Many people already pursuing these improvements



For jet physics, many analytic tools very promising - but not fully developed

Goal of Effective Theory Approaches

Basic goal:

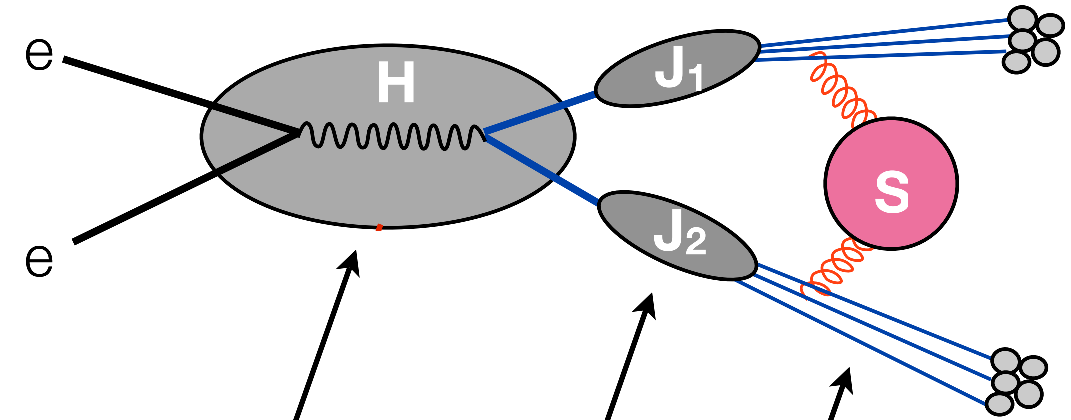
- Sum logarithms of scale ratios

Jet physics has a natural separation of scales:

- Scale of the hard interaction
- Collinear evolution of jets
- Soft inter-jet radiation

Soft-Collinear Effective Theory (SCET) is well suited for jet physics

from Chris Lee



hard function:
short-distance interaction

soft function:
global long-distance interactions

jet function:
collinear evolution of each jet

Factorization and Resummation

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau} = \frac{1}{\tau} H(Q,\mu) J(Q\sqrt{\tau},\mu) \otimes J(Q\sqrt{\tau},\mu) \otimes S(Q\tau,\mu)$$

Factorization divides the cross section up into separate calculable pieces (H, J, S)

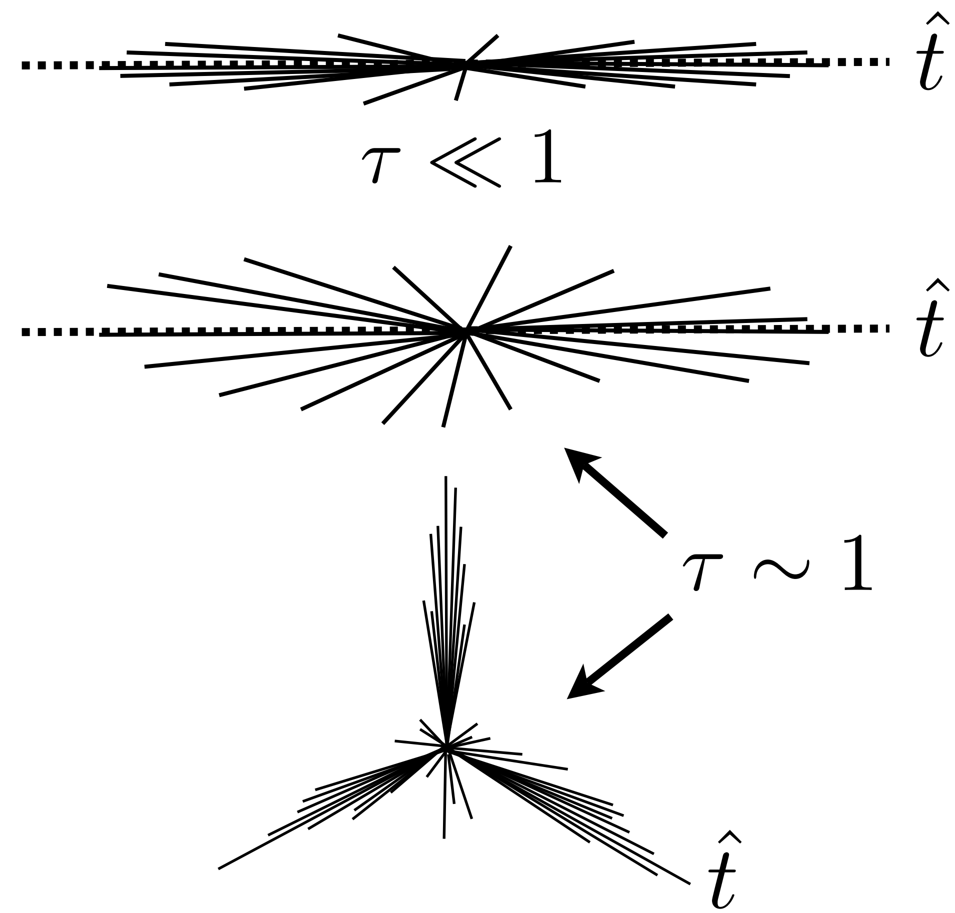
We can separately evolve each function in the factorization theorem - resums the logs occurring in each term in the factorization theorem

$$\tilde{F}(s,\mu) = \tilde{F}(s,\mu_F) \exp\left(\int_{\mu_F}^{\mu} \frac{d\mu'}{\mu'} \tilde{\gamma}_F(s,\mu')\right)$$

H, J, or S (J, S in transform space)

thrust: global 2-jet like measure

$$\tau = \sum_i \frac{E_i - \left|\hat{t}\cdot\vec{p}_i\right|}{Q}$$



Why Resummation Usually Works...

2-jet process

$$\langle 0 | j_{\rm QCD} | q\bar{q} \rangle$$ QCD

IR

UV

Q

$$\mathcal{C}_2(\mu)\langle 0 | \mathcal{O}_2 | q\bar{q} \rangle$$ O_2

2-jet operator

IR

$$\langle 0 | j_{\rm QCD} | q\bar{q}g \rangle = \mathcal{C}_2(\mu)\langle 0 | \mathcal{O}_2 | q\bar{q} \rangle$$

Wilson coefficient C_2 ensures UV of QCD and O_2 match

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Wilson coefficient C_2 ensures UV of QCD and O_2 match

SCET with O_2 in 2 particle states is a scaleless theory

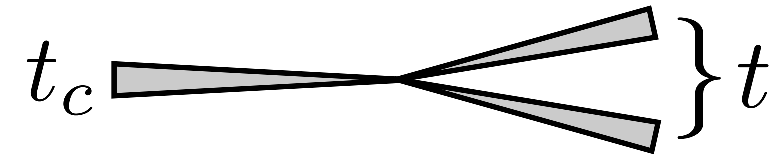
UV = IR

$\Downarrow$

RG (UV evolution) resums logs of observables (IR)

...And Why It May Fail

Describe 3-jet events



$\langle 0 | j_{\mathrm{QCD}} | q\bar{q}g \rangle$ QCD

IR

UV Q

$\mathcal{C}_2(\mu)\langle 0 | \mathcal{O}_2 | q\bar{q}g \rangle$ O_2

IR

UV $\sqrt{t}$

$\mathcal{C}_3(\mu)\langle 0 | \mathcal{O}_3 | q\bar{q}g \rangle$ O_3

IR

SCET with O_2 in 3 particle states is not a scaleless theory

Phase space (IR) logs can exist in O_2 that do not appear in the O_2 UV

$\Downarrow$

RG acts on the UV of a theory

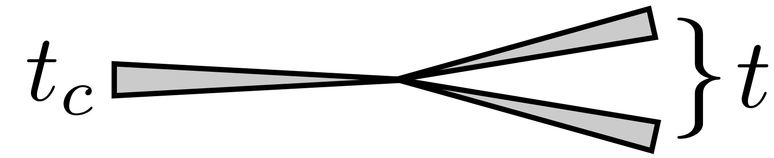
$\Downarrow$

Some logs may not be resummed

...But Probably Not

Bauer, Tackmann, JW, Zuberi

Describe 3-jet events

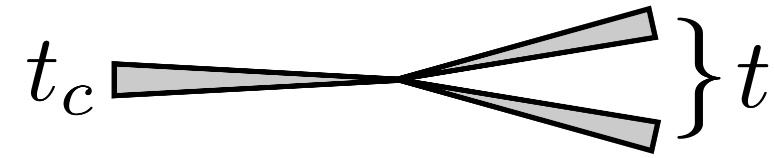


Want to describe $\frac{d\sigma}{dt}(t_c)$

cross section for jets with maximum mass t_c, smallest dijet separation t

...But Probably Not

Describe 3-jet events



Bauer, Tackmann, JW, Zuberi

QCD

Q

$\mathcal{O}_{\text{SCET}}$

$\sqrt{t_c}$

Y

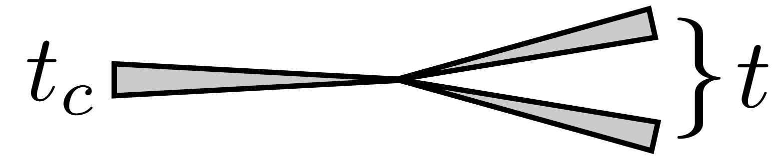
t_c/Q

Want to describe $\frac{d\sigma}{dt}(t_c)$

Below $\sqrt{t_c}$, theory only has soft interactions

...But Probably Not

Describe 3-jet events



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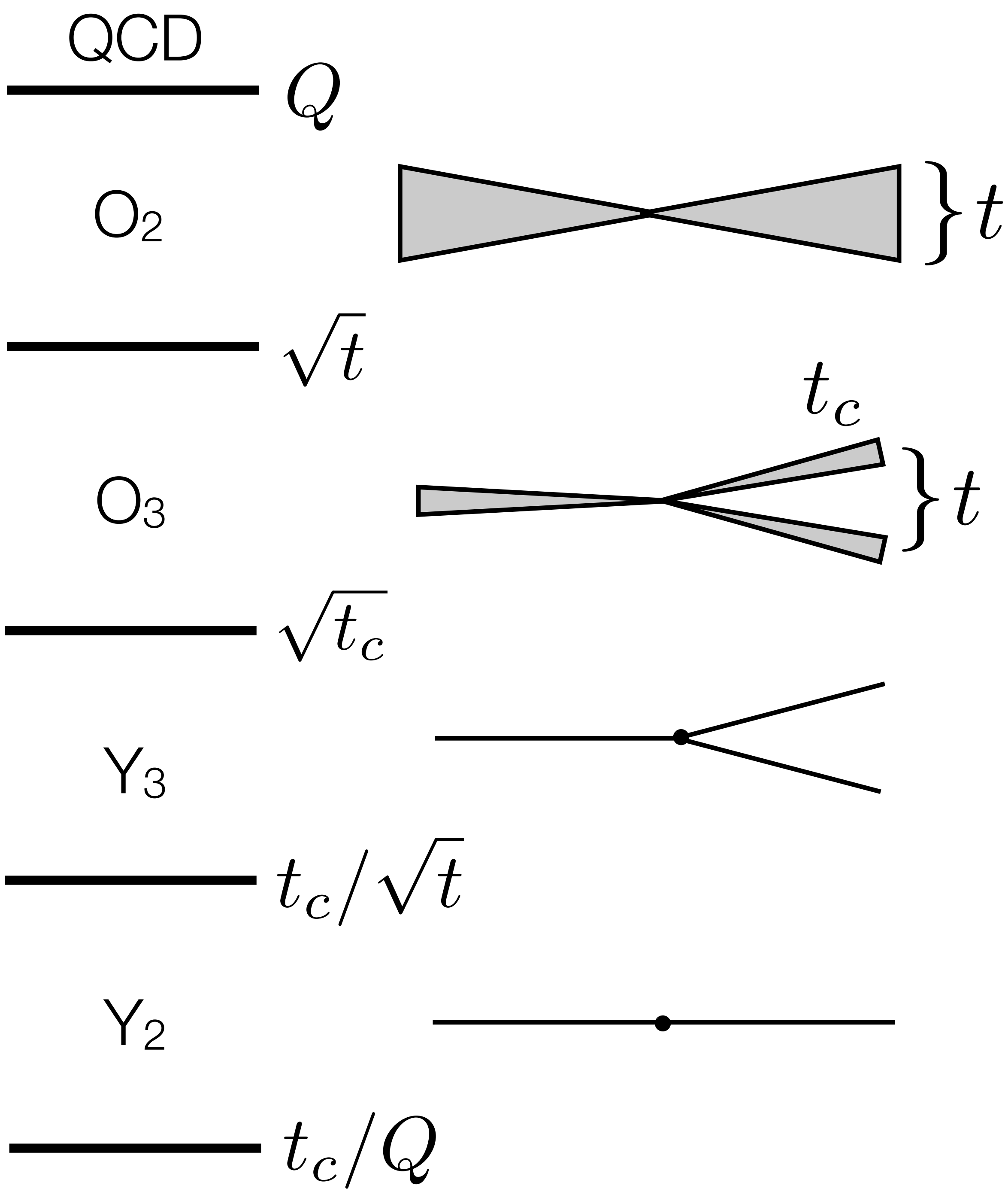


Want to describe $\frac{d\sigma}{dt}(t_c)$

Below $\sqrt{t_c}$, theory only has soft interactions

"missing" parts of UV above $\sqrt{t_c}$ related to the UV below $\sqrt{t_c}$

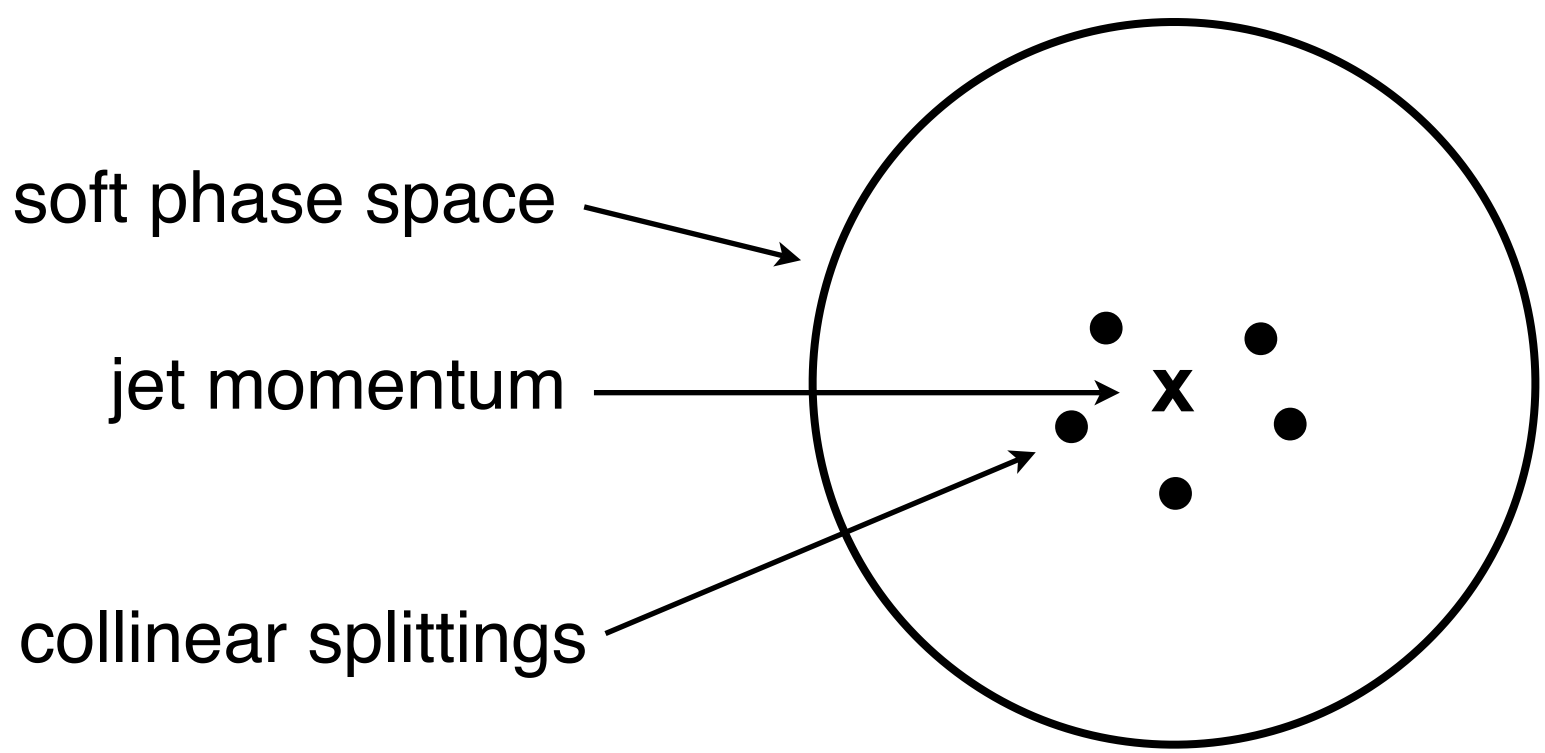
$\Downarrow$

Some (all?) logs of $\sqrt{t_c}$, $\sqrt{t}$ can be resummed

The Jet Algorithm in the Factorization Theorem

The factorization theorem puts constraints on the jet algorithm:

- Jet direction and momentum determined by collinear particles alone - not soft particles
    - Phase space for soft particles must be determined by the jet momentum



a larger jet w.r.t. the size of collinear splittings reduces power corrections

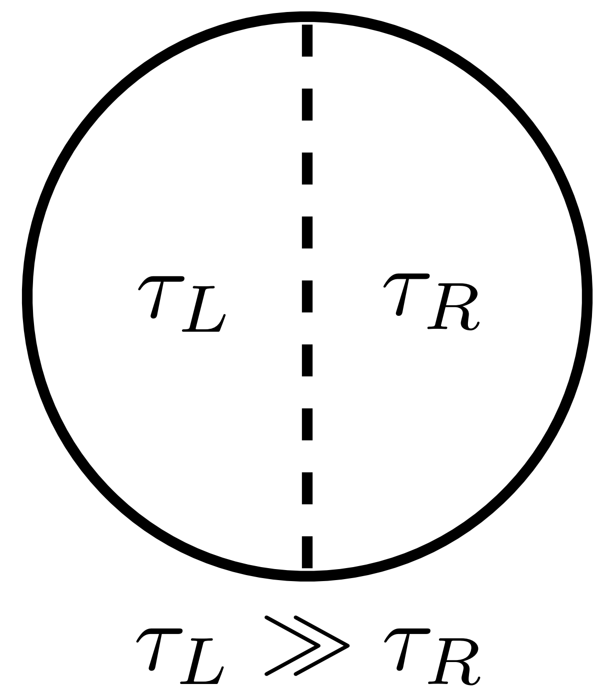
The Jet Algorithm in the Factorization Theorem

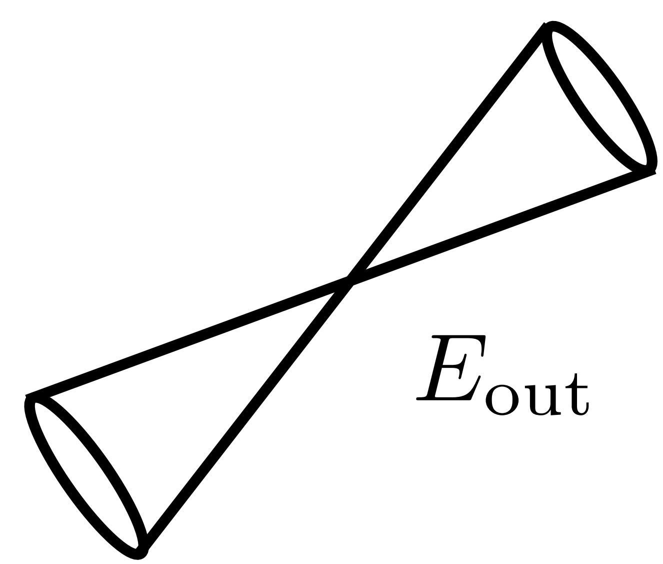
The factorization theorem puts constraints on the jet algorithm:

- Jet direction and momentum determined by collinear particles alone - not soft particles
    - Phase space for soft particles must be determined by the jet momentum
    - Found jets must be insensitive to soft radiation
    - Can parameterize corrections from specific jet algorithms
- Anti-k_T is a very SCET-friendly jet algorithm: collinear particles are recombined first, then soft particles - fixes soft phase space
- This is an “upside-down” view of jets - we hand the jets to the calculation before calculating observables of them

Non-Global Logs

- Non-global observables: dependent on only a region of phase space
  - Many experimental observables are non-global
- Non-global logarithms often not resummed
- Resummation of non-global logs one of the biggest roadblocks to accurate prediction of LHC observables
- Few tools exist to *even understand* the structure of non-global logs (large N_C Monte Carlo, Event2)





Back to the Monte Carlo

- We would like to put more perturbative physics into the Monte Carlo

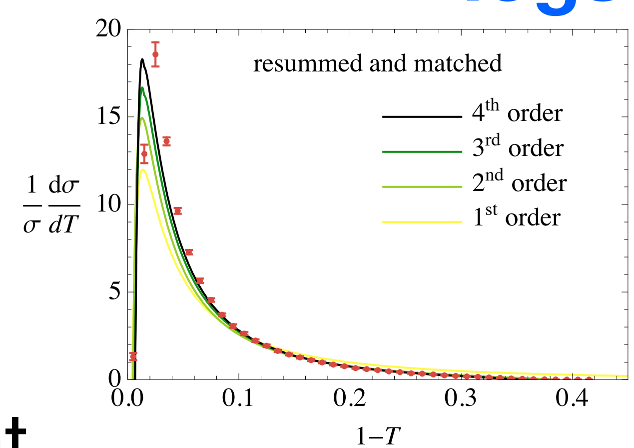
Three ingredients:

- NLO matrix elements
- Matching between different multiplicities
- Correct leading-log integration with parton showers

This is the goal of GenEvA

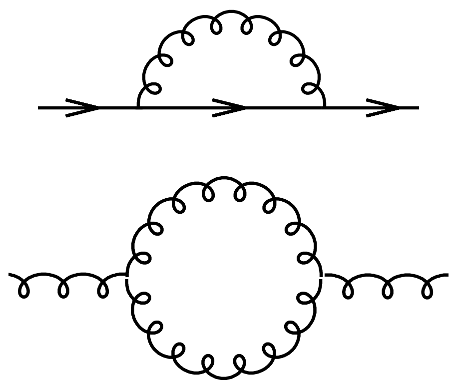
- Most pieces exist - the hard part is the physics in the rest

logs

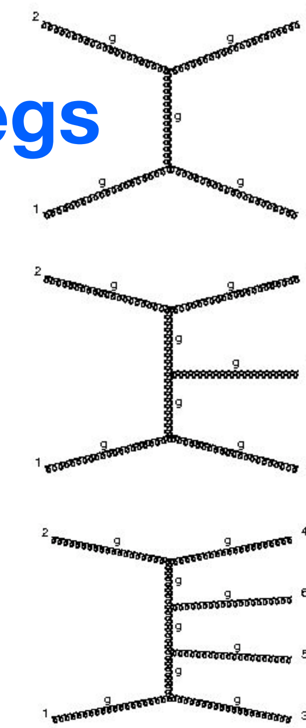


Becher, Schwartz

loops



legs



Summary

- Three common tools for jet physics - Monte Carlo, pheno, analytic
- Monte Carlo and pheno tools well developed, but can benefit from input from analytic methods
- Need to improve analytic approaches to describe interesting observables, e.g.:
  - Understand how to sum non-global logarithms
  - Sum phase space logarithms arising from small jet separations